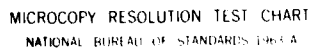END
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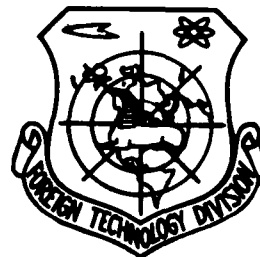MICROCOPY RESOLUTION TEST CHART

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THE CALCULATION OF THE HEAT TRANSFER ASSOCIATED WITH THE
INJECTION OF METHANE GAS AT THE STAGNATION POINT OF THE
DISSOCIATED BOUNDARY LAYER OF THE LAMINAR AIR FLOW

by

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The Calculation of the Heat Transfer Associated with the
Injection of Methane Gas at the Stagnation Point of the
Dissociated Boundary Layer of the Laminar Air Flow

Yan Longhua   Yu Xintian
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ABSTRACT

By using methane gas as the injecting medium, this paper
examines in detail the effect of the chemical combustion
reaction on the heat transfer at the stagnation point of the
laminar flow boundary layer associated with a blunt rotating
object. The following assumptions are made concerning the
characteristic transport properties of the mixed gases. The
Pr and Le numbers as well as $\rho\mu$ are set to be constants.
The boundary layer is assumed to be in a state of thermodynamic
equilibrium. Some calculations are also conducted by treating
the methane gas as an inert gas so that the effect of heat
release associated with the chemical combustion reaction can
be examined by cross comparison.

I.   INTRODUCTION

After the appearance of the thermal ablation phenomenon
at the front section of the material, the thermal environment
around the front section of a supersonic flying object changes

drastically. The change occurs since the speed in which
foreign matter is introduced into the boundary layer is high.
This can decrease the heat flow added on the surface of the
object by its environment. In the same time, however, the
heat flow can also be increased by this added matter if it
undergoes chemical reaction which releases heat within the
boundary layer. Extensive research has been conducted abroad
concerning the computation of heat flow associated with the
chemical reactions of added matters in the laminar flow boundary
layer. For example, references [1] - [3] addressed this problem
by solving the solution numerically. They studied the thermal
ablation of graphite by solving the equations of the stagnation
point of the laminar flow boundary layer in which multiple
sets of elements and combustion reactions exist. Based on
their results, it seems that even though there are many
chemical reaction equations which increase the number of
the system elements and the transport coefficients of the mixed
gases are also increasingly complicated, theoretical study
can still be done with some reasonable or some fixed simplifying
assumptions. The theoretical study can provide insight into
the mechanism of the chemical reactions which affect the thermal
environment. Reference [4] assumed that the transport coefficients
$\rho\mu/\rho_c\mu_c = 1$, Pr = 1 and Le = 1. It applied the combustion area

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model and derived numerical solutions to examine separately
the combustion processes within the boundary layers of a
blunt half sphere and a flat plate, with hydrogen gas as
the injecting medium. In the area of the approximated solutions,
reference [5] proceeded with some general discussion and provided
some qualitative concepts about the equilibrium and the frozen
catalytic wall associated with the chemical reactions of the
added matter at the stagnation point of the laminar flow
boundary layer by assuming $Le = 1$. Similar discussion was also
carried out under the frozen catalytic wall condition of $Le \neq 1$.
For certain materials, such as the mixed gases with Le numbers
close to 1, it also provided the methods for obtaining
approximated quantitative estimates. Reference [6] treated the
carbon combustion problem by using the combustion surface model.
This model, however, lacks generality.

The necessary results obtained from numerical computations
are still incomplete as far as the research of the engineering
computational method is concerned. This is why that this paper
considers the use of methane gas as the injecting medium for
the numerical computation of the combustion of the added matter
at the stagnation point of the boundary layer. The computation
assumes that after methane is injected into the high temperature
boundary layer, the following two major chemical reaction
processes and a decomposition-reconstitution reaction will occur:

$$CH_4 + 3O_2/2 \longrightarrow CO + 2H_2O \qquad (1)$$

$$CO + O_2/2 \longrightarrow CO_2 \qquad (2)$$

$$O_2 \longrightarrow 2O \qquad (3)$$

---

*This paper was presented at the Huang Mountain Thermal Conducting Material Science Meeting in October, 1981.

When the static temperature is not much higher than 4000K, we can reluctantly neglect the effect of the decomposition of the nitrogen molecule. H_2O will not be decomposed into hygrogen and oxygen and all other possible chemical reactions will be treated as of only secondary importance and hence neglected. At the stagnation point, the velocity is zero so we can assume that the chemical reaction mentioned above will be at equilibrium state. The method for computing the transport coefficient of some element (such as methane) is unknown so we assume that l, Pr and Le to be constants. The limited computational examples use the charac'ristic conditions of a flow temperature $T_s = 5000K$ at the stag ion point and a pressure P which equals one atmosphere.

II. BASIC EQUATIONS AND TREATMENT METHOD

Starting from the equations of continuity, element diffusion and energy (13)-(15) as well as the equation of motion (17) associated with the basic equations of a laminar flow boundary layer of a rotating body in decomposed gases derived by reference [7] , we can apply the following

transformation by neglecting the thermal diffusion

$$\eta = (r u_c / \sqrt{2\xi}) \int_0^y \rho \, dy,$$

$$\xi = \int_0^x \rho_c u_c \mu_c r^2 dx \qquad (4)$$

and we can introduce the dimensionless variables $f_\zeta = u/u_c$, $g = (h + u^2/2)h_s$, $f = \int_0^\zeta f_\zeta \, d\eta + f(0)$, $\theta = T/T_s$. Using a method similar to that in reference [7] , we can further use the conditions of the air flow at the stagnation point and the shape of the object to convert the equations mentioned above into a set

$r \doteq x, \; u_c^2 \ll h_s, \; u_c \doteq (du_c/dx)_s x;$

of ordinary differential equations with dimensionless coefficients (this will automatically be satisfied after the transformation of the continuity equation):

$$[(lLe/Pr)C_{i\eta}]_\eta + fC_{i\eta} = \omega_i,$$
$$i = 1, 2, \cdots 7 \qquad (5)$$

$$[(l/Pr)g_\eta]_\eta + fg_\eta + \{[l(Le - 1)/Pr h][\Sigma(h_i - h_i^0)C_{i\eta}]\}_\eta = 0 \qquad (6)$$

$$(lf_{\eta\eta})_\eta + ff_{\eta\eta} + (\rho_c/\rho - f_\eta^2)/2 = 0 \qquad (7)$$

In these equations the subscripts " ζ " represent the derivatives taken with respect to ζ . Here we have already assumed that the diffusion coefficients D_i of all the system elements are the same. In other words, the Lewis numbers are the same. Other symbols include the enthalpy $h = \Sigma C_i(h_i - h_i^0)$, $h_i = \int_0^T c_{pi} \, dT$, ω_i - the mass formation rate of the i-th system element in the chemical reaction, T - temperature, ρ - density and C_i - the mass concentration of the i-th system element. The chemical symbols, molecular weights and the formation enthalpy h_i (also called the reaction heat) of the i system elements are shown in Table 1. h_s is the total enthalpy. The subscript "c" indicates the condition at the outer fringe of the boundary

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layer while the subscript "s" indicates the condition at the stagnation point. The meaning of the two are the same here.

1、组元 i	1	2	3	4	5	6	7
2、化学符号	CH_4	CO_2	CO	H_2O	O_2	O	N_2
3、分子量 M_i	16	44	28	18	32	16	28
h_i^0	1118	2137	943	3211	0	-3693	0

Table 1. The molecular weights and the formation enthalpy (h_i^0 , cal/kg) of the constituent elements within the boundary layer.

1. constituent element i   2.   chemical symbol

3.   molecular weight

We will now further assume that Le $(= \rho D \bar{c} p / \lambda$) is a constant. This is different from the actual condition. The differences between the maximum values and the minimum values of the diffusion coefficients associated with different constituent elements can be quite large, sometimes exceeding 40%. The precise computation has two difficulties: the computational method for the calculation of our desired gas transport coefficients at high terperatures is still being studied and the equations for the computation of the transport coefficients are extremely complicated. The solutions of the main equation sets will be difficult to obtain if we were to consider this problem. It will take several more computations

and it is not advantageous for any preliminary study. Similarly, we assume that $\rho\mu$ = constant, with μ being the viscosity coefficient. We also assume that Pr = constant, with Pr $=\mu\bar{c}_p/\lambda$, λ is the thermal conductivity coefficient , $\bar{c}_p=\sum c_i c_{pi}$ and $\ell=\rho\mu/\rho_c\mu_c$ = 1. In order to compensate for the deficiency of the ℓ = 1 assumption, we have selected several different constants for ℓ in the computation. We have also treated Pr and Le in a similar fashion.

We assume that there are three chemical reactions occurring simultaneously within the boundary layer and they all reach chemical equilibria. There are a total of seven constituent elements and the nitrogen gas does not participate in the chemical reaction. In this way, each constituent element should satisfy three mass reaction principle relationship equations corresponding to the three chemical reactions (1)-(3) as:

$$\frac{C_2 C_4^2}{C_1 C_3^{1.5}} = \frac{K_{P_1}}{M_P^{0.5}} \frac{M_1 M_4^2}{M_2 M_3^{1.5}} \tag{8}$$

$$\frac{C_2}{C_1 C_3^{1.5}} = \frac{K_{P_2} M_2 M_P^{0.5}}{M_1 M_3^{0.5}} \tag{9}$$

$$\frac{C_6^2}{C_5} = \frac{K_{P_3} M_6^2}{M_P M_5} \tag{10}$$

Here $M_p = \sum \left[C_i/M_i \right]^{-1}$. These three relationship equations can substitute the three equations in (5).

Within the boundary layer which contains the seven constituent elements, as long as the mass flow is fixed, the four chemical elements H,C,O and N will be conserved regardless of the condition of the chemical reaction. This is due to the principle of conservation of mass for a closed system. We will

now introduce four new mass quotients of similar chemical elements as : $\widehat{C}_1 = \widetilde{C}_H = C_1 + 0.5 M_1 C_4/M_4$; $\widehat{C}_2 = \widehat{C}_c = C_2 + C_1 M_2/M_1 + C_3 M_2/M_3$; $\widetilde{C}_5 = \widetilde{C}_0 = C_5 + 2 C_2 M_5/M_2 + 1.5\ C_3 M_5/M_3 + C_6$; $\widetilde{C}_7 = \widetilde{C}_N = C_7$. The mass formation rate corresponding to these four values are zero. We can thus obtain four relationship equations as: $\omega_1 + 0.5\ \omega_4\ M_1/M_4 = 0$; $\omega_2 + \omega_1 M_2/\ \ + \omega_3 M_2/M_3 = 0$; $\omega_5 + 2\ \omega_2 M_5/M_2 + 1.5\ \omega_3 M_5/M_3 + \omega_6 = 0$; $\omega_7 \ \cdot\ $. We can now combine the diffusion equation (5) according to the fashion of these four relationship equations and obtain four more new equations.

$$[(\eta Le/Pr)\tilde{C}_{j\eta}]_\eta + f\tilde{C}_{j\eta} = 0$$
$$j = 1, 2, 5, 7 \tag{11}$$

The general solutions of these four equations are similar. We can establish three relationship equations as

$$\frac{\tilde{C}_1 - \tilde{C}_{1w}}{\tilde{C}_w - \tilde{C}_{1w}} = \frac{\tilde{C}_2 - \tilde{C}_{2w}}{\tilde{C}_w - \tilde{C}_{2w}} = \frac{\tilde{C}_5 - \tilde{C}_{5w}}{\tilde{C}_w - \tilde{C}_{5w}} = \frac{\tilde{C}_7 - \tilde{C}_{7w}}{\tilde{C}_w - \tilde{C}_{7w}} = G(\eta) \tag{12}$$

The subscript "w" here indicates the condition at the surface of the wall. By differentiating these equations with respect to l and applying the relationship between the corresponding boundary conditions, we can transform them into the following three new equations.

$$C_2/M_2 + C_3/M_3 = C_4/(2M_4)$$
$$C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 = 1 \tag{13}$$

$$\frac{C_2}{M_2} + \frac{C_6}{2M_6} + \frac{C_5}{2M_5} + \frac{C_3}{M_3} + \frac{C_4}{2M_4} \tag{14}$$

$$= \frac{\tilde{C}_w M_7}{M_5 \tilde{C}_w} \frac{C_7}{M_7} = \frac{0.2095}{0.7808} \frac{C_7}{M_7} \tag{15}$$

We can use these three equations to substitute any three equations

in (11). We will select and retain the equation

$$[(lLe/Pr)\tilde{C}_{2\eta}]_\eta + f\tilde{C}_{2\eta} = 0 \tag{16}$$

We can ultimately obtain the numerically solvable ordinary
differential equations (6), (7), (16) and the algebraic
equations (13)-(15), (8)-(10). After going through the
transformation (4), we can write the corresponding boundary
conditions of the differential equations as :

$$\eta = 0: f_\eta = 0,$$

$$f = f_w = -(\rho V)_w \sqrt{2\rho_w\mu_w(d\eta/dx)},$$

$$g = g_w, \quad f_\eta(M_2/M_1 - \tilde{C}_{2w}) = (lLe/Pr)(\tilde{C}_{2\eta})_w$$

$$\eta \to \infty: f_\eta \to 1, \quad g \to 1, \quad \tilde{C}_2 \to 0$$

Under an outer flow temperature of 5000K, we should
consider the contributions of the molecular translation,
rotation and degrees of freedom of oscillation on the isobaric
specific heat of the i constituent elements. The effect of the
electron excitation energy can be neglected. In order to
simplify the computational equations, we will use the following
approximated equations with errors less than 2% :

$$c_{p1} = 2.4894 - 0.60869(\theta^{-0.5} + 0.5\theta)$$

$$c_{p2} = 0.41032 - 0.04936(\theta^{-0.5} + 0.5\theta)$$

$$c_{p3} = 0.37966 - 0.04166(\theta^{-0.5} + 0.5\theta)$$

$$c_{p4} = 1.003 - 0.05131\theta - 0.20263\theta^{-0.5} \tag{C}$$

$$c_{p5} = 0.31319 - 0.02319(\theta^{-0.5} + 0.5\theta)$$

$$c_{p6} = 0.311$$

$$c_{p7} = 0.3856 - 0.045846(\theta^{-0.5} + 0.5\theta)$$

In this way we can compute $\bar{c}_p$. From the three dimensionless
parameters obtained from the combination of the transport
coefficients of the mixed gases , we now select certain combinations

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of the following values: set ℓ to be 0.5,1,1.5 and 2; set Pr to be 0.5, 0.71 and 1; set Le to be 1, 1.4, 2 and 4. Based on the assumptions mentioned earlier, we will take $\ell = 1$, Pr = 0.71 and Le = 1.4 as the basic condition.

We then apply the computational method of thermal chemistry to obtain the chemical equilibrium constants associated with the chemical reaction equations (1)-(3). In order to simplify the computations, we will use the following approximated equations at temperatures below 8000K :

$$\lg K_{p_1} = 27835./(T_\beta) + 3.9056$$
$$\lg K_{p_2} = 14483./(T_\beta) - 4.3919 \qquad (D)$$
$$\ln K_{p_3} = 16.354 - 61530/(T_\beta)$$

We can now numerically compute the ordinary differential equations along with their boundary conditions and the algebraic equations.

We can obtain the heat flow transferred into the object based on the energy equilibrium between the upper and the lower surfaces of the object [5]. After going through transformation (4), we can then obtain a heat flow computational equation similar to that in reference [7] .

$$q = \frac{\sqrt{2} \, l \, h_i}{Pr} \left\{ g_i(0) + \left[\sum_{i=1} \frac{h_i - h_i^0}{h_i} (Le - 1) c_{iq} \right]_{\omega} - l_{\omega} \frac{Pr}{l} \frac{(h_{i\omega} - h_i^0) - h_{\tau}}{h_i} \right\} \left[\rho_{\omega} \mu_{\omega} \left(\frac{du_i}{dx} \right)_i \right]^{1/2} \qquad (E)$$

The relationship equation for the frictional coefficient is:

$$c_i R_{\infty}^{2} . 2 = \sqrt{2} \, H_{eq}(0), \quad R_{ei} = \rho_{\omega} u_i x / \mu_{\omega}. \qquad (F)$$

III.   DISCUSSION OF THE RESULTS OF THE COMPUTATIONS

The conditions of having a temperature of 5000K at the outer fringe of the stagnation point boundary layer and a stagnation point pressure of 1 atmosphere are comparable to the conditions of an object flying at an altitude of thirty thousand meters with a Mach number of 15. We will now assign exclusively the "basic condition" as the variation in the properties of the stagnation point boundary layer when the dimensionless parameter $-f_w$ increases from 0 to 0.533 under the conditions that $\ell = 1$, $Pr = 0.71$, $Le = 1.4$ and $\theta(0) = 0.4$. We will now proceed with the discussion based on five different types of local modifications of the "basic condition".

1. <u>Basic Condition</u>   In the absence of the injection, the heat flow at the stagnation point of the laminar flow boundary layer can be computed based on equation (63) in reference [7] . We can obtain $q_0 = 1816 \left[\rho_c \mu_c (u_{cx})_s \right]^{0.5}$. With a small amount of methane leaking from inside the wall, the methane will burn on the surface of the wall instantly since the wall temperature is higher than the ignition temperature of methane. The heat released from this process will be added directly on the surface of the wall, causing the transfer of heat flow to the surface of the wall to increase sharply with the increase in $-f_w$. This kind of phenomenon can be observed in Figure 1. For example, when $-f_w = 0.02$, $q = 2109 \left[\rho_c \mu_c (u_{cx})_s \right]^{0.5}$. This value is obviously greater

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than the value of q_o. When $-f_w$ increases very significantly, the oxygen on the surface of the wall is not enough for the total oxidation of methane. The excess methane will enter the middle section of the boundary layer and the combustion within the boundary layer will be most intense and there will be the largest amount of heat released from this process. For example, when $-f_w = 0.533$ the local maximum temperature within the boundary layer is 7300K, exceeding the temperature at the outer fringe of the layer. Different from the phenomenon of the burning of methane on the surface of the wall, this combustion heat will not be transferred directly onto the surface of the wall. The heat will only be transferred to the surface of the wall after a certain range of molecular diffusion and heat convection. By increasing the amount of the injection, we can thicken the boundary layer and hence reduce the heat transfer onto the surface of the wall. By combining these two effects, we can see that the heat flow actually transferred to the wall surface will be slightly lower than the maximum heat flow generated by burning on the surface of the wall. When $-f_w = 0.533$, the heat flow can be 43% lower than the q_o associated with the case of no injection. Except for values near the critical amount of injection, the heat flow decreases roughly linearly with the increase in the amount of the injection. We can also say that the decrease in heat flow is proportional to $(-f_w)^{0.782}$. We will call the amount of the injection that corresponds

to the maximum heat flow associated with the burning process
on the surface of the wall   the critical injection amount
$-f_w^*$. Based on $C_1(0) = C_5(0) = C_6(0) = 0$, we can use the
algebraic equations and the boundary conditions to solve for
the values of the other concentrations on the surface of the wall.
By following this procedure, we have obtained $\widetilde{C}_2(0)$ and $-f_w^* = 0.0556$.
The result is shown in Figure 1 as the peak of the solid line.
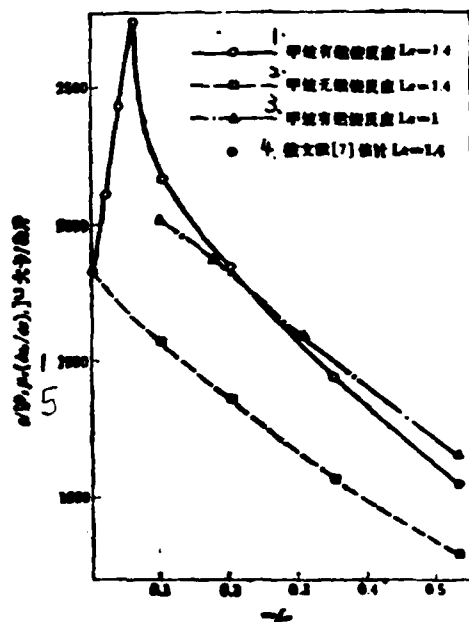

Figure 1.   The variation of the thermal coefficient on the surface
            of the wall with the injection parameter $-f_w$ in the
            presence and in the absence of the combustion reaction
            associated with the injection of methane at the stagnation
            point of the boundary layer.

The conditions are $\ell = 1$, $Pr = 0.71$ and $\theta(0)$.

1. methane with combustion reaction Le $= 1.4$

2. methane without combustion reaction Le $= 1.4$

3. methane with combustion reaction Le $= 1$

4. according to reference [7] and an estimated Le $= 1.4$
5. cal/kg

---

2. Assume methane is an inert gas for the basic condition

This assumption is made so that the combustion heat release
effect can be examined. We set $C_2 \cong C_3 \cong C_4 \cong 0$, eliminate
equations (8)-(10) and then solve the remaining equations. The
dashed line in Figure 1 is a result of the monotonic decrease
of heat flow with $-f_w$. The heat flow in this curve is low
comparing to that in the solid line. The difference in the value
of the heat flow between the case in which combustion exists and the
case with no combustion   reflects the effect of the release
of the combustion heat. The difference in heat flow generally
increases when $-f_w$ increases to $-f_w^*$. Its maximum value is
1090 $[\rho_c \mu_c (u_{cx})_s]^{0.5}$, equivalent to 60% of q_o. As shown by
the solid line in Figure 2, the difference in heat flow becomes
smoother with any further increase in $-f_w$. The dashed line in
Figure 2 shows the ratio between heat flow associated with
combustion and that associated with no combustion.

3. Let Le $= 1$ in the basic condition

The last term of the energy equation vanishes under this assumption, hence making the equation easier to solve. The result of the heat flow computed for this situation is shown as the dot-dash line in Figure 1. When $-f_w > 0.1$, this heat flow is close to the solid line. $Le = 1$ has very small influence on the equation, the type of temperature cross section is similar, the difference in the numerical values is small and the ultimate difference in heat flow is not high. All these indicate that the special case where $Le = 1$ can reflect the characteristics of the cases where $Le \neq 1$.

4. <u>Let the temperature on the wall surface   vary in the basic condition</u>

The result of the computation is shown by the solid curve in Figure 3. The variation in heat flow is less than 6% when the wall temperature varies from 1500K to 3000K. This indicates that the influence of the wall temperature on the heat flow is not large.
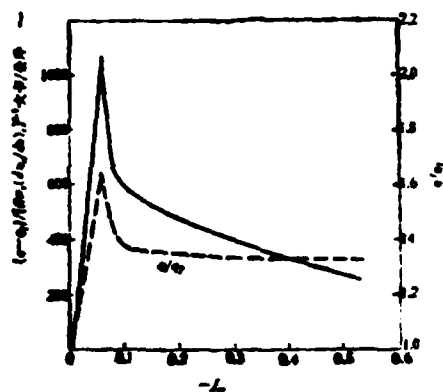

Figure. 2. Differences in heat flow values between the case

Key: 1- cal/kg

with combustion and the case without combustion, with
methane as the injecting medium. This figure also shows
the multiplication factor of the increased heat flow
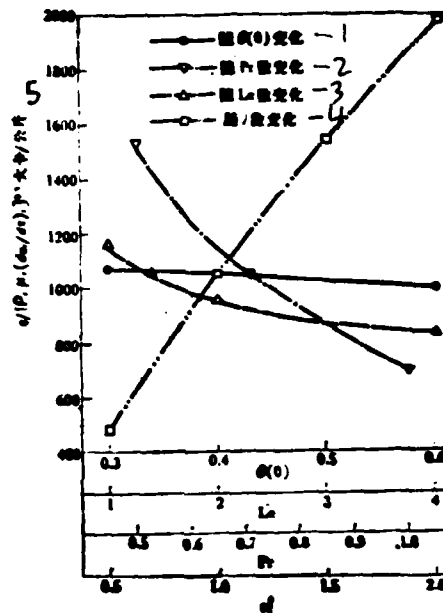associated with the situation where combustion exists.

Figure 3. The variation of the heat flow on the wall surface
with a single basic parameter, with the conditions
that the basic parameters are fixed to be $l = 1$,
$Pr = 0.71$, Le $= 1.4$ and $\theta(0) = 0.4$ and $-f_w + 0.533$

1. variation with $\theta(0)$ 2. variation with Pr
3. variation with Le   4. variation with l
5. Cal/kg

5. <u>Let $-f_w = 0.533$ in the basic condition and observe</u>
   <u>separately the effects of ℓ , Le and Pr</u>

Figure 3 shows the heat flow curve associated with
$0.5 \leq \ell \leq 2$ (double dot-dash line). The heat flow will increase
more quickly with the increase in ℓ . We can say that it is
nearly directly proportional to $(1.965 - 0.744\ell)$. This result
primarily reflects that fact that the increase in the viscosity
coefficient will cause an increase in the frictional coefficient,
hence affecting the energy exchange. The dashed line in Figure 3
shows the heat flow associated with $1 \leq Le \leq 4$. The heat flow
decreases gradually with the increase in Le, nearly directly
proportional to $Le^{0.224}$. This result mainly reflects the
reduction of enthalpy and the gradient of enthalpy on the wall
surface while the temperature gradient increases slightly. The
combined effect causes the heat flow to decrease. The dot-dash
line in Figure 3 shows the heat flow associated with $0.5 \leq Pr \leq 1$.
The heat flow decreases rapidly with the increase in the Pr
number, nearly directly proportional to $Pr^{0.84}$. This result
mainly reflects the simultaneous reduction of the enthalpy
and temperature gradients on the surface of the wall, hence
reducing the energy exchange. The momentum exchange, however,
increases slightly.

The reason why we are considering the effect of the

individual variations of ℓ, Le and Pr on the heat transfer

is to try to compensate for the drawback that the real

values of the transport coefficients can not be determined.

After obtaining the estimates based on other methods, we can

estimate the heat flow by interpolating the curves shown in

Figure 3.

The discussion of the conclusion mentioned above remains

to be examined by future experiments and more accurate theories.

The transport coefficients also need more further studies.

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